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ASTROMETRIC DISCOVERY OF GJ 802b: IN THE BROWN DWARF OASIS?

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ABSTRACT

The Stellar Planet Survey is an ongoing astrometric search for giant planets and brown dwarfs around a sample of $\sim$30 M dwarfs. We have discovered several low-mass companions by measuring the motion of our target stars relative to their reference frames. The lowest mass discovery thus far is GJ 802b, a companion to the M5 dwarf GJ 802A. The orbital period is 3.14 ± 0.03 yr, the system mass is $0.214 \pm 0.045\ M_{\odot}$, and the semimajor axis is 1.28 ± 0.10 AU or 81 ± 6 mas. Imaging observations indicate that GJ 802b is likely to be a brown dwarf with the astrometrically determined mass $0.058 \pm 0.021\ M_{\odot}$ (1 σ limits). The remaining uncertainty in the orbit is the eccentricity that is now loosely constrained. We discuss how the system age limits the mass and the prospects of further narrowing the mass range when e is more precisely determined.

Subject heading: stars: low-mass, brown dwarfs

1. INTRODUCTION

The Stellar Planet Survey (STEPS) is an astrometric search for low-mass companions to M dwarfs. Astrometry provides the most direct measurements of total system and component masses in planetary and binary systems. Even so, the results are dependent on the parallax and the mass of the primary, the latter often derived through the mass-luminosity relationship (MLR). Independent knowledge of the primary mass avoids the degeneracy in the astrometric model between the total mass and the fractional mass: as the total mass increases, the fractional mass can decrease to create the same astrometric signal.

Still, the uncertainties in the parallax and the MLR for main-sequence dwarfs are typically far less than the *additional* uncertainties that arise in model calculations of brown dwarf (BD) and planetary masses from physical principles alone. When we measure their masses, we test and assist the development of the models based on parameters such as age and metallicity. Determining an accurate mass thus deepens our understanding of the fundamental physics of stars and substellar objects. Another direct benefit is to advance our knowledge of the MLRs for such objects to guide further research. At present there are no extant observational MLRs for BDs, and the MLR for stars at the bottom of the main sequence is based on only 10 objects (Henry et al. 1999). We have made several mass measurements of companions to M dwarfs with STEPS (Pravdo & Shaklan 2003; Pravdo et al. 2004 and 2005, hereafter P04 and P05). In each case the combination of astrometry and imaging resulted in conclusions about the masses of the components that could not have been reached by either technique alone.

Hundreds of low-mass objects have been discovered and studied since the advent of sensitive infrared programs such as 2MASS. These objects comprise a significant fraction of the stellar population and mass (e.g., Burgasser 2004). Classification systems for late M (Kirkpatrick et al. 1991, 1995), L (Kirkpatrick et al. 1999), and T dwarfs (Burgasser et al. 2002) have made remarkable progress. Spectral and mass models have followed (e.g., Chabrier et al. 2000; Burrows et al. 2000; Baraffe et al. 2003). The discoveries of BDs in systems (Reid et al. 2001; Freed et al. 2003; Close et al. 2003; Burgasser et al. 2003; Siegler et al. 2003; Golimowski et al. 2004; McCaughrean et al. 2004) have led to more robust estimates of masses, but there are currently few dynamical mass measurements of L and T dwarfs (Buoy et al. 2004; Zapatero Osorio et al. 2004; Close et al. 2005).

2. OBSERVATIONS AND RESULTS

2.1. *Astrometry*

GJ 802 (=LHS 498, G231–13; Wolf 1084) is an M dwarf with the properties listed in Table 1. We observed GJ 802 from 1998 to 2004 with the STEPS instrument mounted at the Cassegrain focus of the Palomar 200 inch (5 m) telescope. The first observation was 1998 July 3.4 = JD 2,450,997.9. P04 and P05 give more detailed descriptions of the instrument and data analysis.

Table 2 shows the results of our measurements of parallax and proper motion. Our parallax is measured relative to the in-frame reference and should be corrected for the reference frame's finite distance. It is consistent with the currently accepted value (Table 1), with or without the addition of the 2 mas correction from relative to absolute parallax for average fields at this Galactic latitude and apparent magnitude (van Altena et al. 1995). Our proper-motion values are also consistent with prior results at slightly more than 1 σ, where the error bars on the prior results are estimated from the variation among past observers (Luyten 1979; Harrington & Dahn 1980; Bakos et al. 2002). In principle, our proper motions should be corrected for the average proper motion of the field, but this is a small effect and does not contribute to errors in the analysis below.

TABLE 1
GJ 802 Known Properties

Parameter	Value
R.A. (J2000.0)[a]	$20^h43^m19^s.41$
Decl. (J2000.0)[a]	$+55°20'52''.0$
V[b]	14.69
J[c]	9.563 ± 0.023
H[c]	9.058 ± 0.019
K[c]	8.753 ± 0.013
Type	dM5e
Parallax[d]	63 ± 5.5 mas
Proper motion[e]	1915 ± 13 mas yr^{-1}
Position angle[e]	27°.6 ± 0°.6

[a] Bakos et al. (2002).
[b] Weis (1988).
[c] 2MASS.
[d] Van Altena et al. (1995).
[e] Luyten (1979).

TABLE 2
STEPS Astrometric Measurements of GJ 802

Parameter	Value
Relative parallax	61 ± 2 mas
Proper motion	1933 ± 1 mas yr^{-1}
Position angle	27°.0 ± 0°.1
Period	3.14 ± 0.03 yr
Total mass	0.215 ± 0.045 $M_\odot$
Semimajor axis	1.28 ± 0.10 AU
Eccentricity, e	0.56 ± 0.30
Inclination	80°.5 ± 1°.5
Longitude of ascending node[a]	17°.5 ± 3°.5
Primary mass, $M_{\rm pri}$	0.160 ± 0.03 $M_\odot$
Secondary mass, $M_{\rm sec}$	0.057 ± 0.021 $M_\odot$

Note.—Epoch and argument of the periapse are not meaningfully constrained.
[a] Or +180° because of into or out of plane ambiguity.

GJ 802 has a periodic astrometric signal after subtraction of parallax and proper motion from the total motion, indicating the presence of a companion, GJ 802b. Figure 1 shows the astrometric data superposed on an orbit with an acceptable fit. Our error estimates comprise the uncertainty due to the Poisson statistics of the image photon counts added in quadrature to 1.0 mas systematic errors. We determine the 1 σ confidence limits in our observed parameters via the method described in Lampton et al. (1976) for multiparameter estimation.

2.2. *Adaptive Optics Imaging*

We use an imaging observation to further constrain the system. We performed H-band adaptive optics (AO) observations with the Palomar 200 inch system (Troy et al. 2000) on 2004 June 6 and September 2 UT. Figure 2 shows the resulting image of GJ 802 from September. The conditions were excellent on both nights, with subarcsecond seeing. We also show a comparison image of GJ 1210 that reveals its binary nature (P05), obtained during the June run. The failure to detect GJ 802b with AO rules out a companion within 3.25 H magnitudes (5%) of the primary. The components were separated by ~100 mas during the AO observation (Fig. 1), i.e., were capable of being resolved (Fig. 2).

3. DISCUSSION

3.1. *The Primary*

GJ 802A is a field M dwarf 15.9 pc from the Sun. It is active, classified as dM5e, with both Hα (Reid et al. 1995) and X-ray emission (Hünsch et al. 1999). Its (U, V, W)-space velocity is consistent with the local volume–complete sample of M dwarfs studied by Reid et al. (1995), although it is slightly farther away. Independent knowledge of the age and mass of the primary would be helpful in further constraining the properties of this system. An estimate of the age based on the $V - I_{\rm C}$ color at which such stars become active is ~6 Gyr (Hawley et al. 2000). If we assume that all the light comes from the primary, its mass inferred from the V MLR (Henry et al. 1999, eq. [7]) is consistent at the 1 σ level with that inferred from the H MLR (Henry & McCarthy 1993, eq. [3a]): $M_{\rm pri}(V) = 0.150^{+0.022}_{-0.029}\ M_\odot$ and $M_{\rm pri}(H) = 0.174^{+0.023}_{-0.020}\ M_\odot$. If the mass of the secondary takes its maximum acceptable value of 0.08 $M_\odot$ (see following section), then $M_{\rm pri}(V)$ is reduced by only 0.001 and $M_{\rm pri}\ (H)$ is reduced by only 0.003 $M_\odot$. We therefore adopt $M_{\rm pri} = 0.16 \pm 0.03\ M_\odot$ (cf. Close et al. 2005 for another view of the MLR accuracies).

Bonfils et al. (2005) give metallicity distributions of M-dwarf stars in the solar neighborhood. If we use their equation (1) to determine the metallicity of GJ 802A, we find [Fe/H] = 0.025 if all the V- and K-band light came from the primary, and [Fe/H] = −0.042 in the other extreme, if the light were evenly divided between the components. However, if we apply their MLR (eq. [2]) to this system, we find that it predicts a mass on the low end of our range for the primary, $M_{\rm pri} = 0.13$, if it contains all the light. To get a mass more consistent with other MLRs would require [Fe/H] = 0.25, the upper limit of their range of validity. We conclude that there is no evidence for nonsolar metallicity, but a question remains about the consistency of the MLRs.

3.2. *The System*

Our astrometric measurements yield the orbital parameters subject to two ambiguities. First, the scale of the system is not uniquely determined because we do not resolve the components. Thus, for a given period, the data admit a range of values for the semimajor axis a and total mass $M_{\rm tot} = M_{\rm pri} + M_{\rm sec}$. This is shown in Figure 3. The open diamonds show only the acceptable fits to the data after ~11,000 Monte Carlo trials. The y-axis of Figure 3 is our observed parameter, $(f - \beta) = \alpha/a$, where $f = M_{\rm sec}/M_{\rm tot}$, the fractional mass, β is the fractional light, and α/a is the ratio of the photocentric to Keplerian orbits (e.g., P04). Second, the value of $(f - \beta)$ can be the same in two very different physical situations. If the secondary is small in mass compared to the primary, we have $f \ll 1$, $\beta \sim 0$, and $(f - \beta) \sim f \ll 1$. Conversely, if the secondary is close in mass to the primary, we have $f \sim 0.5$ and $\beta \sim 0.5$, but also $(f - \beta) \ll 1$.

Fortunately, we can use other information to resolve these ambiguities. The total mass of the system is bounded by the mass limits on the primary based on its spectrophotometry. Additionally, the values for f and β are related by a MLR. A current observational V-band MLR (Henry et al. 1999) is based on stars with masses from 0.074 to 0.178 $M_\odot$. Since the V light contribution is negligible for masses ≪0.08 $M_\odot$, we create a $\beta = 0$ region that allows us to extend the curve for the Henry et al. MLR into the BD range (Fig. 3, *solid line*). We also illustrate a 5 Gyr model from Baraffe et al. (2003) that already extends throughout the BD realm (Fig. 3, *filled circles*). The MLRs agree well with each other below the peak of $(f - \beta)$. The fits to the STEPS data that overlie the MLRs represent the orbital models consistent with all the currently known information.

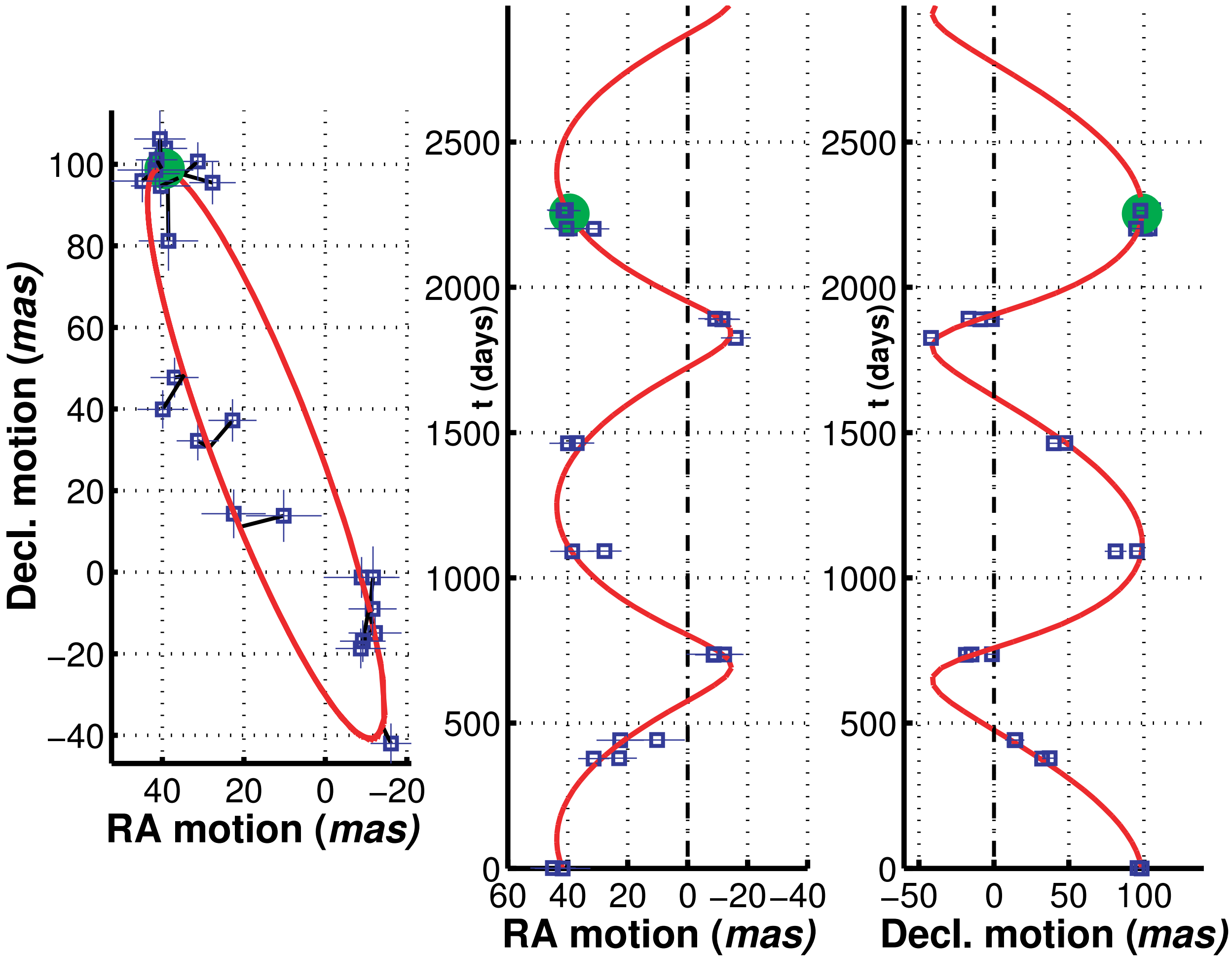

FIG. 1.—STEPS data (*points*) are superposed on a model of the Keplerian circular orbit (*solid red lines*). The right ascension and declination dimensions vs. time are shown separately. The 1 σ error bars on the points are our photocentric measurement errors multiplied by the ratio of the Keplerian to the photocentric orbit. The position of the AO observation is also shown (*green filled circle*).

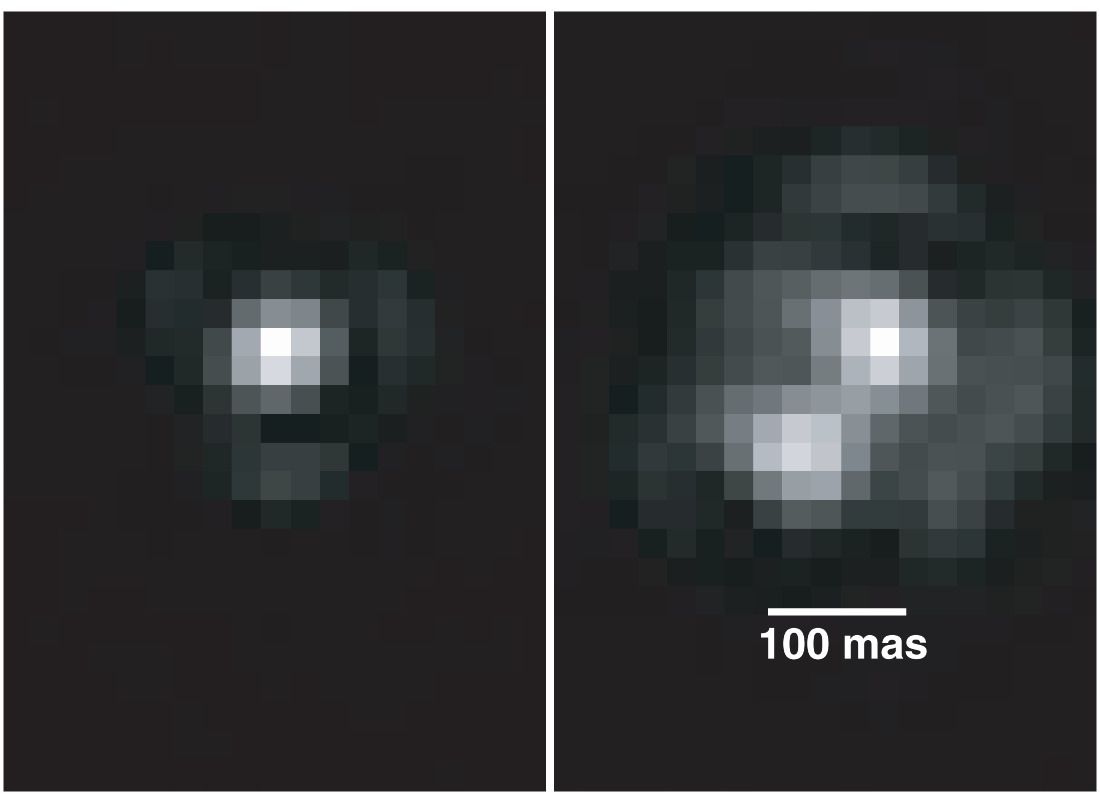

FIG. 2.—Palomar 200 inch AO image of GJ 802 (*left*) and GJ 1210 (*right*). The scale is the same for both images.

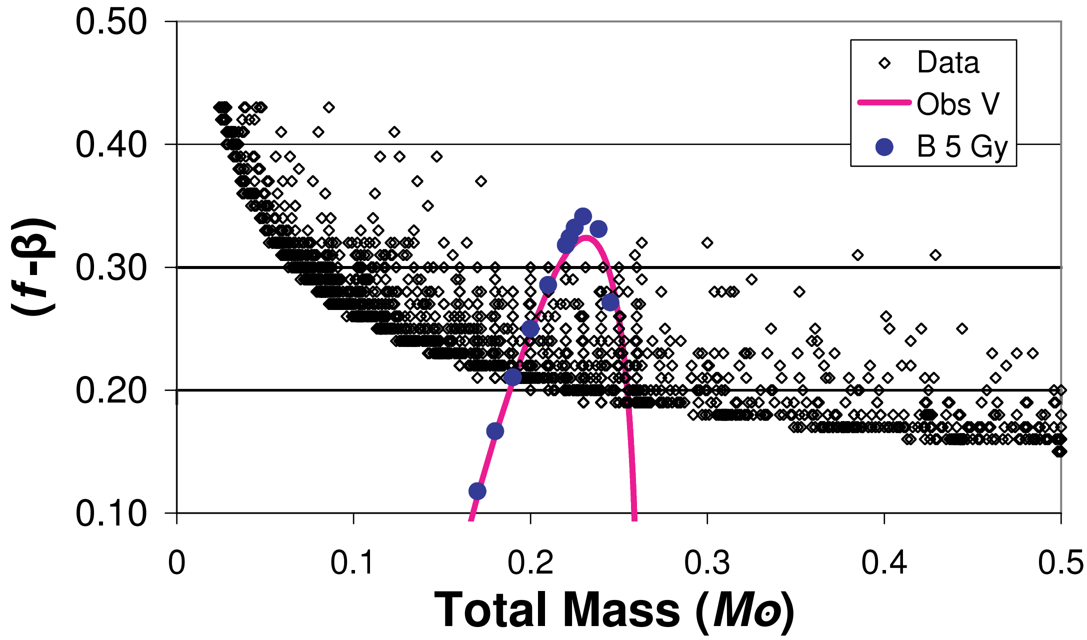

FIG. 3.—Points show the results of ∼11,000 Monte Carlo trials for the GJ 802 orbit (*open diamonds*). We plot $(f - \beta)$ vs. M_{tot} for all models falling within the 1 σ confidence limits. Superposed on the data are the composite MLR curve in the V band based on observations (Henry et al. 1999; *solid line*) and the MLR points (*filled circles*) from the model of Baraffe et al. (2003).

The fact that the MLRs in Figure 3 have two M_{tot} values for each $(f - \beta)$ illustrates the second ambiguity mentioned above. These are the high ($f \sim 0.5$) and low ($f \ll 1$) mass branches. However, our AO observations eliminate the high-mass branch. The M_H of the GJ 802 composite source is 8.05, based on the 2MASS measurement and the parallax (Table 1). The M_H of GJ 802b is then >11.36, based on our AO observation. This value is ∼3 times fainter than that for the lowest applicable mass of the H-band MLR for late M dwarfs (Henry & McCarthy 1993) and implies a secondary mass $M_{sec} < 0.08\,M_{\odot}$. The implied V luminosity of such an object compared with the total V luminosity of GJ 802 results in $\beta < 0.024$. This also places it in the ascending portion of the $(f - \beta)$ function and rules out the high-mass branch. Figure 4 shows the GJ 802 H-band

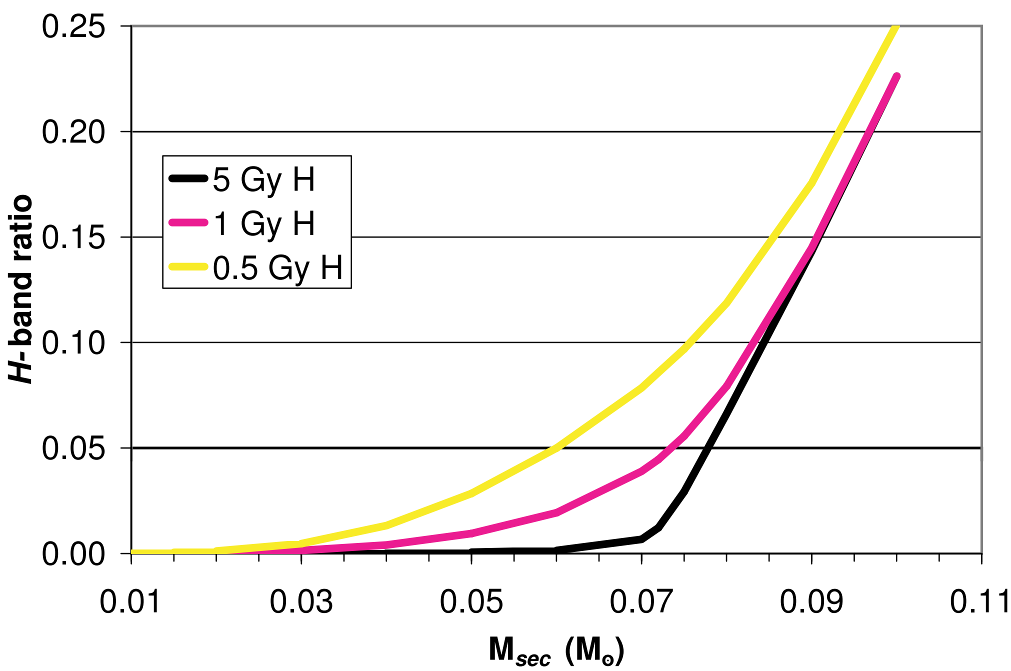

FIG. 4.—H-band ratios for different system ages based on the models of Baraffe et al. (2003).

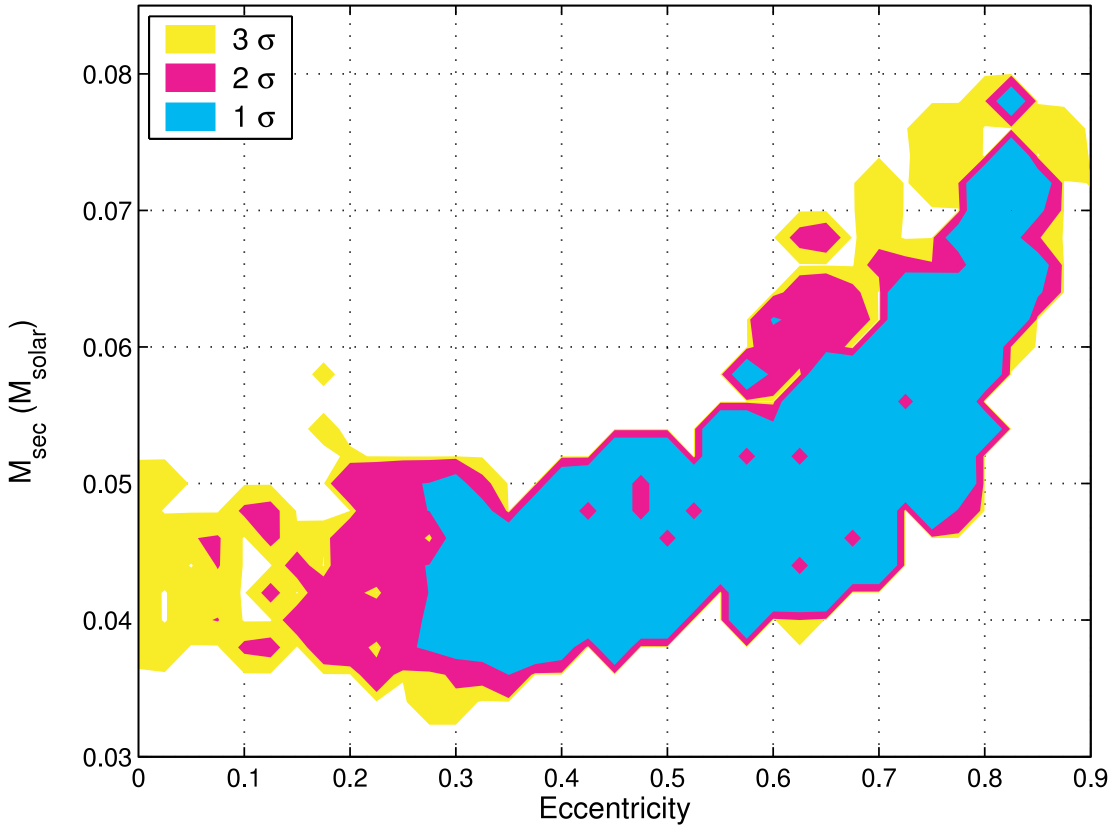

FIG. 5.—Secondary mass M_{sec} as a function of eccentricity e for models with 1, 2, and 3 σ confidence limits.

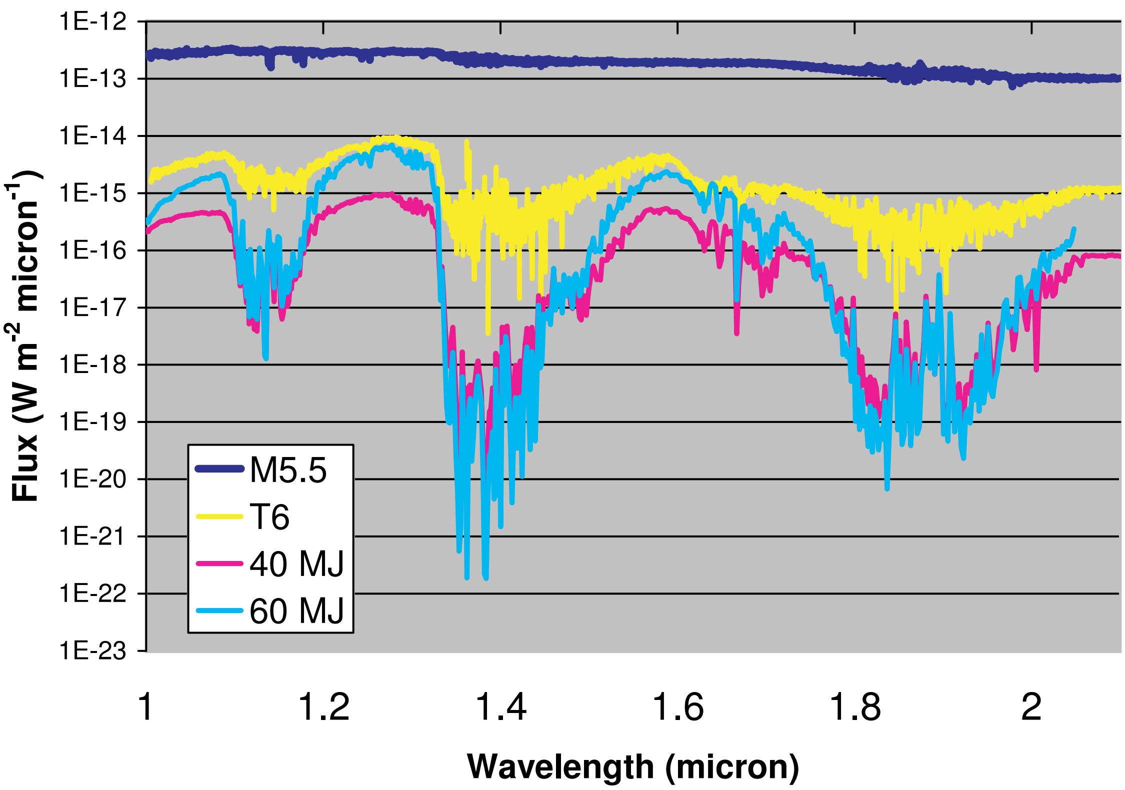

FIG. 6.—Comparison of the near-IR spectra normalized to 10 pc of an M dwarf (M5.5), a late T dwarf (T6), and two models for age 5 Gyr BDs with masses of $40M_J$ and $60M_J$. The observed spectra are from McLean et al. (2003) and the models from Burrows et al. (2002, 2003).

secondary-to-primary ratios for the Baraffe BD models. Values greater than 0.05 for the H-band ratio are ruled out by our AO observations. Therefore, for the ages of BDs shown, mass values to the right of where the curves intercept 0.05 are ruled out. The upper limits are 0.078, 0.073, and 0.060 $M_{\odot}$ for 5, 1, and 0.5 Gyr, respectively. The 5 Gyr upper limit is probably applicable based on other indicators of the system age (see § 3.1). Another version of the MLR (Delfosse et al. 2000) is applicable only in the high-mass branch shown in Figure 3 and results in estimates $\sim$0.025 $M_{\odot}$ higher that the other models shown.

Table 2 lists the orbital parameters. The major remaining uncertainty in the orbit is the eccentricity e. The mass of GJ 802b is dependent on e, as shown in Figure 5, and is now constrained to be 0.057 ± 0.021 $M_{\odot}$ (37–82 Jupiter masses, M_J).

3.3. *GJ 802b*

There are a number of observational possibilities to further constrain the mass of GJ 802b. Continuing STEPS astrometry will succeed if we are able to obtain observations at a critical phase to distinguish among different values of e. The current uncertainty in e is due to an unfavorable temporal beating between the observational opportunities and the period. Even limiting the eccentricity to values less than 0.5 will reduce the mass upper limit to 0.05 $M_{\odot}$ ($52M_J$). Additionally, a *Hubble Space Telescope* (*HST*) NICMOS imaging observation with its high spatial resolution and sensitivity in the *JHK* region can measure not only the separation and position angle of the system but also the flux ratio for many BD models (e.g., P04). Figure 6 illustrates the relative spectra in this band normalized to a distance of 10 pc for an M dwarf similar to GJ 802A, a late T dwarf, and models for $40M_J$ and $60M_J$ BDs at age 5 Gyr. Primary-to-secondary *JHK* flux ratios will be in the 30–200 range for different BD spectral types.

BDs are both X-ray (Rutledge et al. 2000) and Hα emitters (e.g., Tsuboi et al. 2003). GJ 802b might be detectable in Hα at *HST* spatial resolution if the emission were as large as the 1–10 Å equivalent width measured for other BDs, and at a contrast ratio of $\sim$100. The X-ray emission is not yet separately measurable because current instruments are limited to $\sim 1''$ spatial resolution. However, with another factor of $\sim$10 in spatial resolution the companion would be detectable if it reached, for example, the peak of the flaring X-ray emission from the 0.5 Gyr brown dwarf LP 944-20, $\sim 10^{26}$ ergs s^{-1}, or $\sim$1% of the total GJ 802 emission (Hünsch et al. 1999).

The gains from more accurately measuring the mass of GJ 802b are twofold. First, it will place a point on the BD MLR and continue the determination of that useful research tool. Second, it offers the possibility of acquiring a spectrum to accompany the accurate mass measurement that will guide further model development.

3.4. *The Brown Dwarf Oasis?*

The BD desert may prove to be a mirage when one knows where to search. STEPS is unique in its target set of nearby M stars and its ability to astrometrically probe close to the primary at the secondary mass limits described above. We chose all of our targets (excepting a known control) because they were single stars, according to the state of the science in 1997. We have now detected five companions to 24 targets that have sufficient data. Three of the companions are late M stars, two are in or near the BD range (GJ 802b and GJ 164B), and for the others, the existences and masses of potential companions are still pending. Although the STEPS numbers are small, even now the percentages are inconsistent with the presumed BD desert; e.g., <1% of solar-type stars have a brown dwarf within 5 AU (Marcy et al. 2000).

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